J. Moura Pires, M. Pantoquilho, N. Viana (2004)
"Real-Time Decision Support System for Space Missions Control".
Proceedings of The 2004 International Conference on Information and Knowledge Engineering, 21-24 June, Las Vegas, USA.

Real-Time Decision Support System for Space Missions Control

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Abstract - Space weather refers to conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and that affect human life or health[1]. Such influence is particularly strong on spacecrafts by reducing the mission lifetime and causing long periods of instrument's unavailability. Understanding the cause-effect relation between space weather events and spacecrafts anomalies is a very important task but also a very complex one, which requires a multidisciplinary approach and is a long-term goal. Meanwhile, nowadays most mission control teams are supported by different and non-integrated systems providing telemetry and space weather information. However, they require better information availability, integrating space weather and spacecraft data, including past, current and forecasted data. This paper outlines a decision support system which in addition to the data integration, also provides efficient tools to analyse off-line data, monitor real-time space weather and spacecraft parameters and events, infer spacecraft anomalous conditions based on the uninterrupted real-time analysis of the spacecraft status parameters and to build predictions for any space weather or spacecraft parameter through the use of artificial neuronal networks and physical models. Such a system is under development for the European Space Agency control centre.

Keywords: Decision Support, Aerospace, Data Warehousing, Real-time

1. Introduction

This paper outlines a Space Environment Information System (SEIS) which is mainly a decision support system that provides flight control teams with useful space weather information (past, current and forecasts) to increase the ability to protect spacecraft components from hazardous events and therefore increase the instruments measurement time-window and prolong the lifetime of satellites.

The system’s main goal is to support flight control teams in taking decisions about how to react to space weather conditions possibly causing spacecraft degradation. Furthermore, it will increase the knowledge and awareness of how space weather affects satellite performances.

To fully understand the context, which motivated the presented system, a brief explanation of the space weather phenomena, is included.

The paper is organized in the following way: section two introduces the space weather hazardous environment and potential harms to spacecraft; section three presents the SEIS decision support system, describing the addressed spacecraft missions, the system overall architecture and detailing the design and technological options. The fourth section presents the conclusion and future work and in the last section, a table with the acronyms used in this document are presented.

2. Space Weather Impact

Space weather refers to conditions on the sun and in the solar wind, magnetosphere, ionosphere, and thermosphere that can influence the performance and reliability of space-borne and ground-based technological systems and that affect human life or health [2].

The sun is the main driver of space weather near Earth, although other phenomena with galactic, planetary or even human related origin can also cause space weather effects[3]. Examples of these non-solar sources are galactic cosmic rays, meteoroids, space debris and man-made and planetary radio waves.

The sun is a very active star where frequently solar eruptions, called flares and coronal mass ejections, take place. The number of eruptive events varies with an approximately 11-year cycle. When activity levels are at their highest, the number of explosive events is about 10 times higher than during periods of low activity. These explosive events are the main source of space weather disturbances near the Earth i.e. they are the main drivers of space weather [1, 4, 5]

Our society is becoming increasingly dependent on technology that can be affected by space weather. Satellites are the most susceptible of being affected and damaged by space weather effects. Telecommunication, scientific research, remote sensing and weather satellites can be affected by space weather in very different ways: the surrounding space environment crossed by a spacecraft during its lifetime can strongly affect the onboard systems and can cause hazards such as memory malfunctions and data loss. In extreme cases, not only particular spacecraft instruments but also the whole satellite can be lost. Moreover, astronauts, ground stations, and commercial flights are also within space weather impact range [2]. Space weather is set to become of increasing importance in our daily lives as our dependence on technological systems increases. Satellite control teams must be aware of potential harms to their spacecrafts in order to defend themselves against the hard and auspicious environment changes. Furthermore, ground stations and even commercially driven institutions which deal with telecommunications or other technology areas (e.g. oil pipelines and electric power grids induced currents) susceptible of space weather hazards deserve to have a system that can warn them of upcoming solar storms, magnetic field disturbances or any other space weather effect.

Currently many ground based and space based observatories are closely monitoring space weather. Integrating the information provided by such observatories and making them available in an appropriate format to institutions who depend or are affected by space weather conditions will provide additional knowledge in order to safekeeping their investment.

To know in advance the strike of such an enemy can definitely result in the salvage of precious and very expensive devices such as spacecraft and more important, the preservation of human lives.

2.1. The Role of space weather Awareness

Nowadays, many satellites are currently in mission, which means that we have access to many distinct measurements of space weather components from different spacecrafts having distinct orbits and are therefore taking measurements in different areas of space. Moreover, we have many ground based advanced systems taking the same measurements from different points in the globe. We have spacecrafts passing the same problematic regions and experiencing the same problems at different times.

According to the European Space Agency (ESA), in order to protect spacecrafts, all critical systems are shutdown and shielded for a fixed time window. However, sometimes this time window is excessively large (given the space weather event duration) and an instrument’s observation/broadcasting time can be significantly decreased without a specific need. Often, this time window is smaller than the real space weather event duration causing unnecessary exposure of systems and instruments to high radiation levels without shielding. In either case, we lose: science and industry loses.

Although we already have access to all the information required to take better decisions, that information and knowledge is usually scattered across multiple locations in heterogeneous data formats stored in distinct methods which makes its access difficult and does not allow its correct and most profitable use.

Knowing what is going to happen in advance allows, for example, spacecraft control teams to activate the spacecraft shielding capabilities and re-calculate the entry/exit points in some regions or adjust orbital trajectories.

Having both space weather and spacecraft data available, allows the analysis and determination of possible cause-effect relations between space weather events and spacecraft anomalous conditions. It also allows the study and further understanding of space environment behaviour, thus allowing the improvement of spacecraft manufacturing and mission planning.

Having this as context, an innovative and ambitious project was proposed to ESA: the Space Environment Information System for mission control purposes (SEIS).

This system is introduced in the next section.

3. A Space Environment Information System

The SEIS system is a multi-mission decision support system for mission control purposes. Its main goal is to supplement the flight control team with space environmental information and telemetry data - past, current and forecasts. This information is translated into spacecraft operational impact assessment and suggested recovery operational procedure(s). Such procedures are defined in the spacecraft Flight Operation Plan (FOP) [6].

The envisaged solution consists in collecting historical, real-time and forecasted space weather and spacecraft data coming from multiple data sources deemed relevant for the specific spacecraft operation context.

This system combines different data sources (space weather and spacecraft related) into a single data repository providing information access and analysis over the complete set of data. The main focus of this system is data integration, by fetching, processing and making available data from several heterogeneous data sources in a single storage area. Its design was inspired by traditional business oriented decision support systems based on Data Warehousing storage techniques [7-9], optimized for very large quantities of data and to provide data availability for applications with very distinct time needs: monitoring real-time data and reporting and analysing offline data.

The data is divided into two major categories according to its origin: space weather and spacecraft. In each of these categories, we can find real and forecasted data. The forecasts are generated by either external entities and by the system itself, either through the application of physical models or artificial neural networks. Real and forecasted data comprises time series such as radiation counters, and events, such as solar flares.

The system retrieves, collects and turns available the referred data and also provides a set of tools to analyse and visualize it, according to the time-space requirements of the dataset and the users' needs.

The selection of space weather time series and events was achieved in straight collaboration with several solar physicists (space weather domain experts) in order to include the relevant data to the system. The major space weather data source selected is NOAA[10], which includes real-time readings from ACE and GOES [11] satellites, although several others are being used. The datasets include proton, electron and neutron flux counters, geomagnetic fields' indicators, interplanetary environment parameters, radio bursts occurrences and solar events.

3.1. Spacecraft Missions

Three distinct on-going missions were selected for the spacecraft dataset composition: INTEGRAL – the reference mission, ENVISAT and XMM. Each mission will have a specific purpose in terms of usability and demonstration of involved concepts, and therefore the data collected from them varies according to its goal.

For the INTEGRAL mission [12], launched on October 2002, the SEIS main goal is maximizing the payload instruments' time while operating in safe condition under high radiation levels, which results in an increasing of the instrument's life expectancy and usage, with benefits on the total real observation time while also increasing the instruments' scientific return.

For the ENVISAT mission, an advanced polar-orbiting Earth observation satellite, launched on March 2002, the system will only integrate its Single Event Upsets (SEU) historical database of occurrences [13]. A Single Event Upset is a bit-flip on an electronic memory device. For the ENVISAT satellite, which has an orbital period of 101 minutes, the SEUS's rate is approximately eight per orbit. For this mission the SEIS's major goal is to provide the tools to explore possible correlations between SEUs occurrences, spacecraft orbital position and specific space weather conditions at spacecraft orbital locations. SEUs' cause determination is an important issue for ENVISAT's flight control team, which prefers to leave the instruments on during these events in order to be able to determine each instrument's degradation factor, than to switch them off.

The last spacecraft mission, from which data will be loaded into the SEIS system, is the XMM science satellite, launched at December 1999 [14]. Data collected from this mission consists of its radiation sensors' telemetry data and its orbital position since the date of launch. Possible benefits for the XMM mission spacecraft will be the exploration of data analysis/correlations of space weather and XMM's telemetry data.

3.2. System Architecture

The SEIS system overall architecture is depicted in Figure 1. The system is composed by:

A major block, named Data Integration Module (DIM), receives and storages data from external data sources and data provided by a forecast module (FM). Prior to storage, the data is transformed, processed and organized to fulfil the requirements of a Monitoring Tool (MT) and Reporting and Analysis Tool (RAT).

The SEIS Forecasting Module provides forecasting capabilities for space weather data, based on well-established physical models, as well as, generic time series prediction based on Artificial Neural Networks (ANN). In addition, the FM also comprises orbital propagator models. All forecasts (space weather and spacecraft) generated by this module will be fed into the DIM.

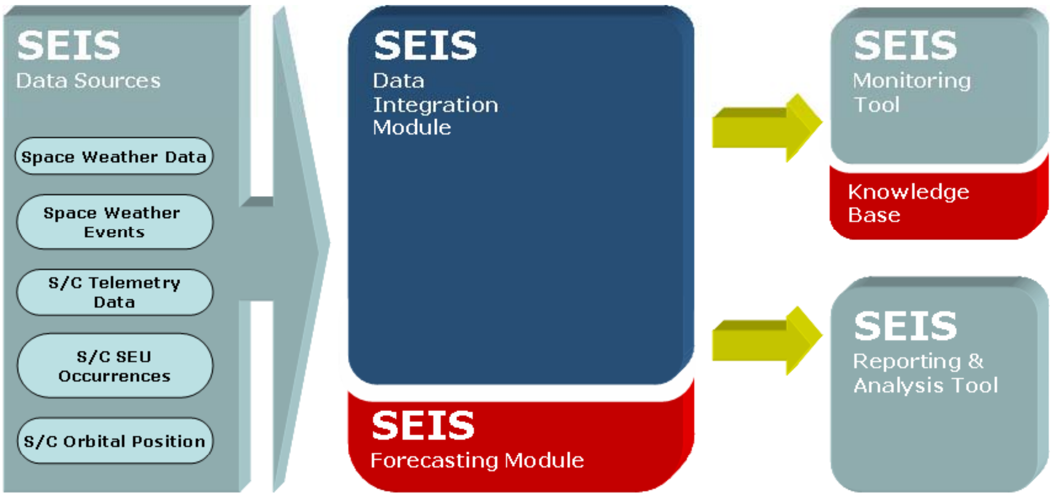

Figure 1: SEIS system overall architecture.

The Reporting and Analysis Tool's (RAT) purpose is to allow exploration of all data stored in the DIM through the use of analytical querying. Report creation capabilities will also be available in order to correlate different data types (real and forecasted space weather and spacecraft data) allowing different data visualization options.

The Monitoring Tool (MT) is an online-oriented tool to near real-time space weather and spacecraft data visualization. If available, forecasts can also be displayed. In addition to monitoring the instruments' status, the tool will also be able to identify possible instrument anomalous conditions and even suggest appropriate recovery actions to be taken in order to minimize spacecraft instrument degradation. The required knowledge, which allows the identification of anomalous conditions (triggering alarms) and suggestion of recovery actions will be extracted from INTEGRAL's Flight Operations Plan (FOP) and represented in accordance with traditional Knowledge Base Systems (KBS), based on production rules and rule inference methodologies.

3.3. Design Options

The DIM is certainly one of the crucial points in the system's design. Having applications with such distinct requirements as the RAT and MT implies the physical division of the data, which is accessible to each one. The solution was the implementation of distinct databases: a data warehouse to hold all the data and to support a multidimensional database for offline analysis and a real-time database specially designed for real-time updates to hold the most recent real-data and forecasted data to support the online monitoring requirements.

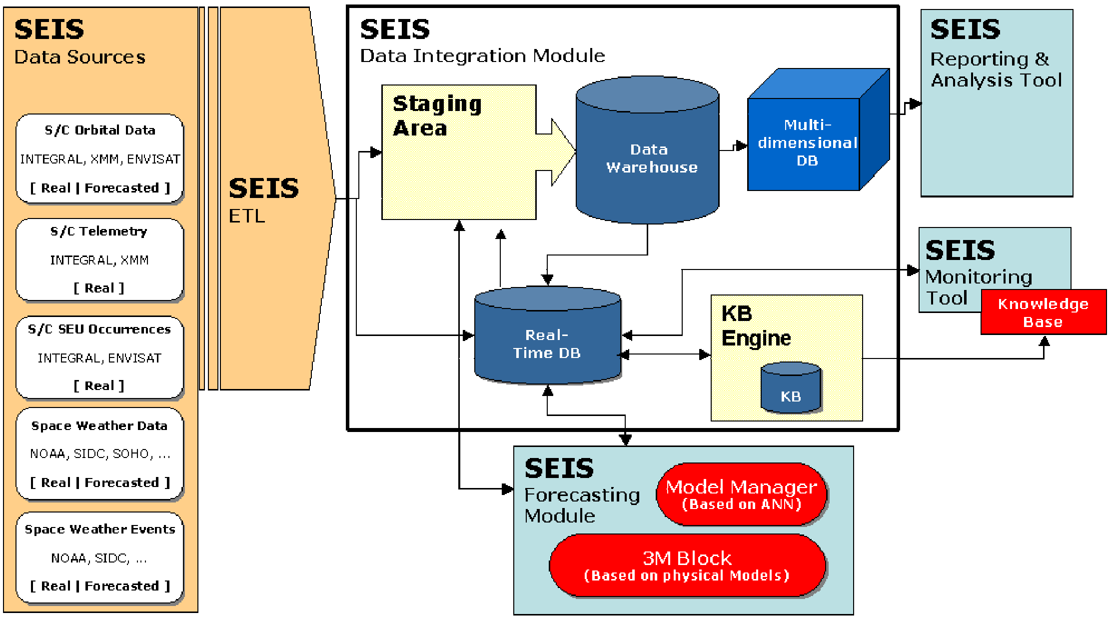

Figure 2: DIM detailed architecture.

The data retrieval process (ETL) will be continuously running (loading new data into the system). Figure 2 depicts the flowing of data occurring in the SEIS system. Data is being fetched from external data sources into the staging area (for later processing) and into the real database. The forecasted data (generated by the FM) and the alarms generated by the knowledge base engine are also stored in the staging area.

All the data to be loaded into the data warehouse is prepared in the data staging area for faster inserts. The multidimensional database is loaded directly from the data warehouse, in which the data is already cleaned and well organized.

All three databases will need to be periodically synchronized, since they do not hold the same information at all times. The real-time database stores about 208 hours of data, being 104 hours of past data (real and forecasted) and 104 hours of future forecasted data, to respond to the MT requirement of presenting at most 84 hours, which can be user configurable to divide between past and forecasted data. The user can select to visualize only 84 hours of forecasts from the current moment forward or 84 hours of past data or any other values in between. We have extra 40 hours divided in 20 for past and the other 20 for future, just to prevent synchronizations delays. The real-time database is updated directly from the external sources and also from the forecasting module and the data warehouse for forecasted data. The data stored in the real-time database, which can also be generated by the KBS Engine, is loaded daily into the data warehouse and at the same time the real-time database forecasting values are loaded from the data warehouse.

The data warehouse will be updated only daily in order to avoid constant service unavailability. Since the data warehouse and the multidimensional database are the support for offline analysis this is a reasonable constraint. For real-time or online data analysis the system provides the real-time database which is updated with new space weather and spacecraft data every 5 minutes.

3.4. Technological Options

In order to deploy the whole SEIS system and its components, several key technologies are being used. We will now briefly describe some of the chosen implementation options.

All space weather and spacecraft related data are stored on three different logical-oriented databases (real-time database, data warehouse and multidimensional database). The database services are supported by Microsoft SQL Server 2000™ and Microsoft OLAP Services™.

The FM is implemented using freely space weather and spacecraft charging effect available models as well as the SPENVIS[15] model package and is being implemented on Fortran/C. The ANN component is based on based on MatLab's Neural Network Toolbox™, which manages and generates generic time series predictions[16] based on Elman's recurrent Neural Networks[17].

The two tools (MT and RAT) are being developed using the .NET framework.

4. Conclusion and Future Work

The major achievements with the presented system are related to the data integration module, which allows the development of the referred services and tools. This data integration is a considerable step towards knowledge inference, considering that the data stored in the system warehouse comprises space weather data and events as well as spacecraft telemetry and events, both real and forecasted. Moreover, the data is loaded at real time. Besides all the data, on-site inferred knowledge from that data is also stored. This achievement is possible with data warehouse and OLAP[18] techniques as well as rule based system concepts.

From this special data warehouse it is possible to develop tools that based on the available data can produce more benefits to their users. The tools to be implemented generate data (Forecasting Module), knowledge (Monitoring Tool) and provide very powerful and useful data and knowledge visualization methods (Monitoring Tool and Report and Analysis Tool). Furthermore, new independent tools can use and benefit from the stored data, through the external access point available in the SEIS.

The integrated data allied to the monitoring and visualization features provided with the two primal tools will allow ad-hoc data analysis as well as assisted data reporting creation, and will provide the users with a real-time spacecraft status assessment and space weather alert tool.

The overall user benefits coming out from the SEIS system usage, include increased awareness of space weather cause & effect relationships; vis-à-vis on-board spacecraft health status; improved productivity and safety levels of satellite operations versus space weather environmental phenomena; increased science return and extended life time.

For future work, we intend to extend the project to other spacecraft missions and apply data mining and statistics techniques to find out relationships and correlations between space weather conditions and spacecraft operational status. For the near future, investigation on how to improve the KBS representation solution to allow the system to provide suggestions to prevent upcoming events is envisaged. The resulting output would be the identification of an action to be taken in response to an upcoming (future) event and related applying date/time.

5. Acronyms

Table 1: Acronyms list.

Acronym	Definition
ACE	Advanced Composition Explorer (satellite)
ANN	Artificial Neural Networks
DIM	Data Integration Module
ENVISAT	Environmental Satellite
ESA	European Space Agency
ETL	Extraction, Transformation and Loading
FM	Forecasting Module
FOP	Flight Operation Plan
GOES	Geostationary Satellite
INTEGRAL	International Gamma-Ray Astrophysics Laboratory (satellite)
KBS	Knowledge Based System
MT	Monitoring Tool
NOAA	National Oceanic and Atmospheric Administration
OLAP	Online Analytic Processing
RAT	Reporting and Analysis Tool
SEIS	Space Environment Information System
SEU	Single Event Upset
SPEnvIS	Space Environment Information System
SQL	Structured Query Language
XMM	X-ray Multi Mission (satellite)

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